FOURIER HOLOGRAPHY FOR ENHANCED VISUALIZATION OF VOLUME PHASE OBJECTS THROUGH EXPLOITATION OF NON-LINEARITIES ASSOCIATED WITH SILVER HALIDE EMULSIONS

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INTRODUCTION

In an effort to enhance visualization of shock fronts associated with single explosive particle (diameter ~ 100μm) detonation, a Fourier holographic recording technique has been developed which relies on film non-linearities to greatly increase phase-object visibility. The driving force behind this work is the investigation of detonation dynamics in dispersed particle explosives. These explosives, used for mine neutralization, are comprised of a fine, solid particulate dust which is dispersed as a cloud in the atmosphere over a given area. When detonation is initiated in some portion of the cloud, the ensuing detonation wave propagates throughout the entire cloud and results in an explosion, generating a tremendous pressure which serves to destroy or render useless any land mines present. Understanding the mechanism by which individual particles interact to sustain detonation in these solid dispersed particle explosives has been the research goal, and has led directly to the development of several holographic techniques.

Early in the research program, pulsed holography was used to determine whether solitary particles detonated when initiated with an IR laser pulse, or whether they simply experienced a rapid burn, termed deflagration. For these experiments, two holographic exposures of the detonating particle were recorded in rapid succession (50ns to 450ns apart). The ability to record two holographic exposures separated so closely in time became possible by introducing a phase-compensating optical delay line (White cell) into the holographic setup. Measurement of the outward propagating shock front diameter for each holographic reconstruction permitted shock front velocity to be calculated, and led to the determination that the solitary particles did indeed detonate and not deflagrate[1].

Subsequent to this finding, two-particle interaction studies began. For this phase of research, the goal was to determine the method by which detonation of one single particle was passed to a second particle in close proximity to the first, essentially to understand how the detonation is communicated from one particle to the next. Possibilities included

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shock wave initiation, plasma initiation, or some combination of the two. Owing to particle size variation and differences in detonation initiation timing between particles, this study required multiple holographic exposures (8-10) to be recorded in rapid succession, essentially creating a holographic movie of the event. To accomplish this, a high speed, time resolved, spatially multiplexed holographic system was developed which permitted up to ten holographic exposures to be recorded at framing intervals adjustable from 28ns to 170ns. This system incorporated a White cell delay line and a custom designed hyperharmonic beamsplitter which provided equal energy for each exposure. With this capability, two particle studies were performed by initiating detonation in one particle, and holographically recording the subsequent shock wave and plasma generation, propagation, and interaction with the second particle[2].

The most recent phase of research has involved studying detonation dynamics in a large collection of dispersed explosive particles (>1000), using a miniature shock-tube designed for clear optical access of the area of interest. Initially, multiple holographic exposures of a shock front passing through such a dispersion were recorded using a variation of the time resolved holographic system mentioned above. It was soon discovered that the quality of the reconstructed images was quite poor, owing to the large number of particles contained within the volume of interest. The reconstructions suffered from depth-of-field noise and speckle noise, which together made it extremely difficult to distinguish individual particles and their associated shock fronts. The recorded holograms contain information from both amplitude and phase objects: the individual particles of explosive and the propagating shock fronts, respectively. In addition, the particles themselves may be translucent, depending on their composition. Such conditions result in a great deal of noise when the shock tube event is back lit during the exposure of the holograms.

The holographic recording technique reported here has evolved in an effort to improve both particle and shock front visibility in the reconstructed holograms by applying optical filtering and holographic techniques. A holographic optical configuration has been designed that records only high spatial frequency information through exploitation of transmittance/exposure non-linearities in the film. When reilluminated, a high-pass filtered image is reconstructed - the background intensity that typically 'washes out' the particles in the field is removed, the details of the objects in the field are enhanced, and phase objects, such as localized changes in air pressure associated with shock fronts, are rendered visible.

OPTICAL FILTERING

One of the most well established techniques for removing and processing image characteristics is through the use of a predetermined filter placed at the spatial transform plane in an optical processor[3-5]. High-pass filtering can be achieved in this manner simply through placement of an opaque disk in the transform plane centered about the optical axis[6], while low-pass filtering is achieved by placement of a doughnut in the transform plane. Each of these methods remove the low or high frequency components, respectively, from the object spectrum by physically blocking the light carrying this information.

Several methods have been proposed to enhance the holographic images recorded using in-line particle holography techniques[7]. Two of the more predominate methods employ schemes that are designed to enhance the carrier fringe contrast of the recorded holograms by means of optically processing the object and reference beams[8,9].

The technique reported here capitalizes on the observed high-pass filtering effect of over-exposed Fourier-type holograms[10]. In our technique, the hologram is recorded in an off-axis configuration, with the holographic plate positioned at the transform plane of a positive lens. Instead of the use of a physical disk to remove the unwanted frequency components, the hologram is recorded such that the influence of the low spatial frequencies is greatly suppressed in the reconstructed image. Since the hologram is recorded at the spatial transform plane, strong low frequency components (such as background illumination and variations in dispersant density) drive the exposure biasing point far into the saturation region of film, thus overexposing it. As a result, the region of film which corresponds to the dc and low frequency components of the object spectrum possess an extremely low transmittance and has very little dynamic range left (if any) to be utilized for recording the interference fringe modulation. Consequently, the diffraction efficiency of the hologram associated with those frequencies approaches zero, effectively removing the low frequency components from the reconstructed image.

PRINCIPLE OF OPERATION

An off-axis holographic set-up is used to record the hologram, as shown in Figure 1. The optical transform of the object volume (O) is achieved by placing the test volume after a positive lens (L1). As stated before, the film plate (H) is positioned at transform plane, which is a focal length behind L1.

By applying principles of Fourier optics to the recording configuration, one may obtain an expression for the interference pattern between the reference and object beams at the film plane. For an object placed a distance f-d behind a lens of focal length f, and assuming that the object is of smaller spatial extent than the illumination, the field distribution at the focal plane, $U_f(x_f, y_f)$, can be written as a function of the object's spatial frequency spectrum $T(f_x, f_y)$[4]:

$$U_f(x_f, y_f) = \frac{A \exp\left[j\frac{k}{2d}\left(x_f^2 + y_f^2\right)\right]}{j\lambda d}\frac{f}{d}T(f_x, f_y) \tag{1}$$

where $f_x \equiv x_f / \lambda d$ and $f_y \equiv y_f / \lambda d$. At the focal plane, this field distribution is interfered with an off-axis plane wave.

The irradiance distribution at the focal plane will be proportional to the magnitude squared of the sum of the field distributions, which can be cast into a general irradiance distribution expression:

$$I = I_b\left(1 + M\cos\left[g(x_f, y_f)\right]\right) \tag{2}$$

where I_b is the average value of the intensity, M is the modulation index of the irradiance pattern, and $g(x_f, y_f)$ is the phase variation across the film plane. For the specific case described here, it can be shown that[11]:

$$I_b = A^2\left[\gamma^2\left|T(f_x, f_y)\right|^2 + K\right] \tag{3}$$

$$M = \frac{2\sqrt{K}\gamma T(f_x, f_y)}{\gamma^2\left|T(f_x, f_y)\right|^2 + K} \tag{4}$$

$$g(x_f, y_f) = \left[\frac{k}{2d}\left(x_f^2 + y_f^2\right) - kx_f\sin\theta\right] \tag{5}$$

where K is defined as the reference-to-object beam power ratio $K \equiv B^2 / A^2$, and, for simplicity, γ as $f/\left(\lambda d^2\right)$.

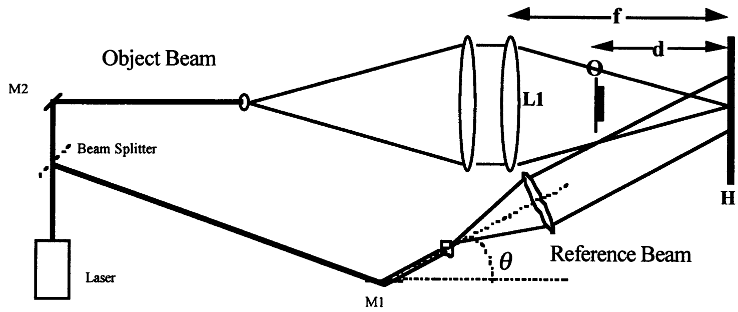

Figure 1. Holographic Recording Configuration: O-Object to be filtered, H-Holographic Film Plate (focal plane of L1), L1-Fourier Transform Lens, d-distance from Object to Film Plate, f- focal length of L1, θ: angle between reference and object optical axes.

The resulting transmittance recorded on the film can be approximated to the first order as[12]:

$$T_A = T_b\left(1 + \beta M \cos\left[\tfrac{k}{2d}\left(x_f^2 + y_f^2\right) - k\, x_f \sin\theta\right]\right) \qquad (6)$$

where T_b is the transmission of the film associated with the biasing exposure, β is the slope of the Transmission-Exposure (T-E) curve at the biasing point, and M is the modulation. For such a case, the diffraction efficiency can be expressed as[12]:

$$\mathrm{D.E.} = \left(0.5\, T_b\, \beta M\right)^2 \mathrm{x}\, 100\% \qquad (7)$$

For the particular case being examined, the bias point selected on the T-E curve will be a function of the irradiance distribution of the object's transform, or:

$$E_b = I_b t_e \propto A^2\left[\left(f/\lambda d^2\right)^2 \left|T\left(f_x, f_y\right)\right|^2 + K\right] t_e \qquad (8)$$

where t_e is the exposure time.

In order to accomplish the high-pass filtering effect, the bias point is chosen such that for strong low frequency components it will be well into the tail of the T-E curve of the film (as shown in Figure 2.) For low power, high spatial frequencies, the bias point will lie on the linear region of the curve. By setting the low frequency bias points far into the tail of the curve, low spatial frequencies will be characterized by both a low value of T_b, and an extremely small value of β. Thus, the diffraction efficiency of those spatial frequencies will be effectively 0%, removing their effect from the reconstructed hologram. High spatial frequencies recorded about the linear region will appear in the reconstruction.

In addition to this "burning out" of low frequency information, it can also be shown that the modulation index M is proportional to the magnitude of the object spectrum:

$$|M| \propto |f_x||f_y| \qquad (9)$$

indicating a linear increase in the magnitude of the modulation index as the magnitude of the spatial frequency increases[11]. Thus, the modulation (M) associated with high spatial frequencies that significantly contribute to the object frequency spectrum will be linearly enhanced, resulting in an improved diffraction efficiency.

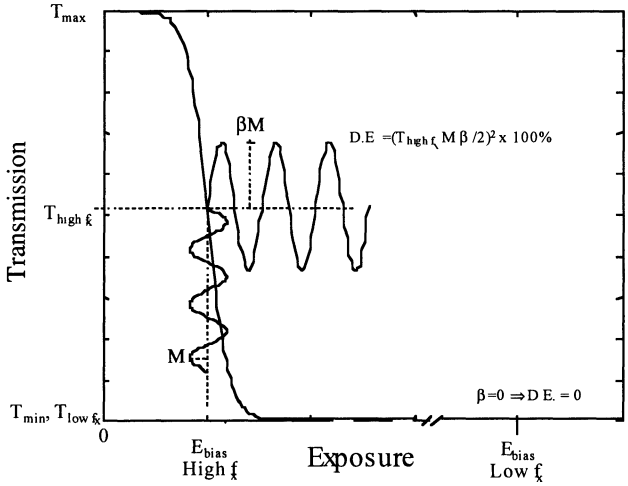

Figure 2. Modulation associated with high/low spatial frequencies, as shown on a hypothetical film T-E curve.

An optical system was assembled as shown in Figure 1. Using this system, both CW and pulsed illumination proof-of-principle experiments were performed. For the first set of experiments, a 10mW CW Nd:YAG laser operating at 532nm was used to illuminate a clear field U.S.A.F. 1951 resolution test pattern. This pattern contains spatial frequencies ranging from 4 to 181 line pairs per millimeter. Holograms of the object were recorded on AGFA 8E56 film plates both with and without the transform lens (L1 in Figure 1) in place. Reconstruction of the standard non-filtered hologram is shown in Figure 3a, while that of the filtered hologram is shown in Figure 3b. These results clearly show the high-pass filtering effect for amplitude-based objects, as well as the consequent reduction in background noise.

A second experiment was performed using a Q-switched Nd:YAG laser operating at 532nm. This experiment was designed to show the high-pass filtering effect for phase objects, such as the high-speed shock front produced by detonation of a single particle explosive. The setup for this experiment was identical to that described above, with the exception that the object was a tungsten electronic probe needle tip, upon which a pulsed IR

a)

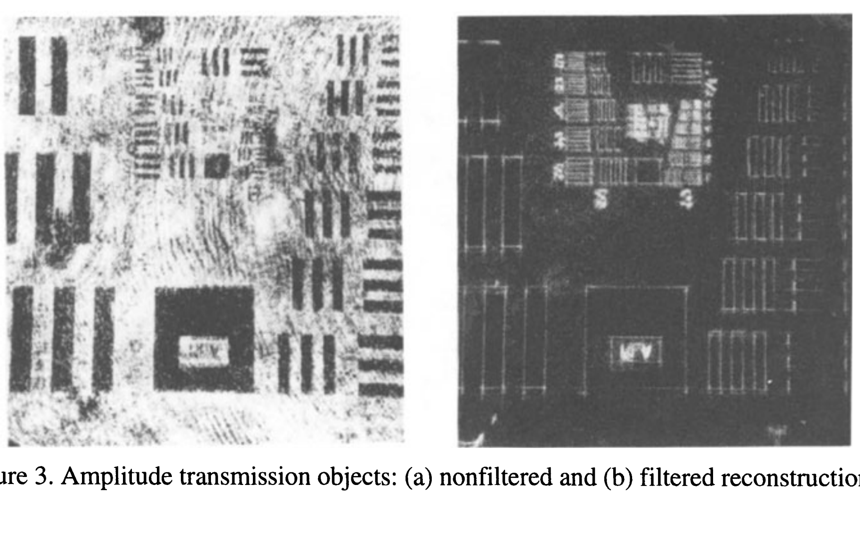

Figure 3. Amplitude transmission objects: (a) nonfiltered and (b) filtered reconstructions.

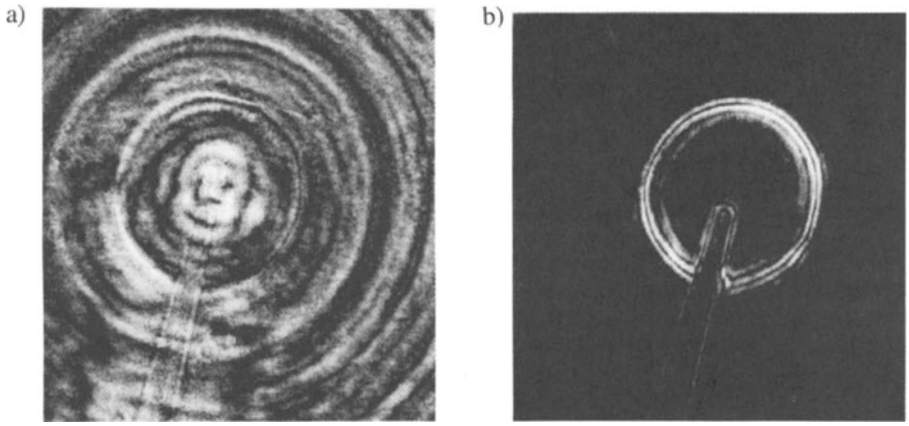

Figure 4. Phase objects: (a) nonfiltered and (b) filtered reconstructions.

laser was focused. Ionization of the air by the pulsed IR laser was the source of the shock front for this experiment. Strictly speaking, the tungsten needle is unnecessary for air breakdown to occur, but it does provide a consistent localization of the effect and a convenient reference when viewing the reconstruction. The hologram was recorded 170ns after firing of the IR pulsed laser. As above, holograms of the object were recorded both with and without the transform lens in place. Reconstruction of non-filtered hologram is shown in Figure 4a, while that of the filtered hologram is shown in Figure 4b. Visualization of the outward propagating shock front emanating from the needle tip is quite clear in Figure 4b, and is an excellent example of the high-pass filtering for phase objects.

EXPERIMENT

To study detonation in an actual solid particulate dispersion, a miniature shock tube was developed which provided clear optical access over the full 3 inch length of the tube. The shock tube was constructed of 0.5" thick aluminum with 0.5" thick Lexan windows for optical access, and was designed such that a particulate dispersion could be blown into the chamber through the shock tube bottom, and laser initiated through a Lexan window in the top (see Figure 5). The dispersion of particles in the tube is accomplished by blasting a

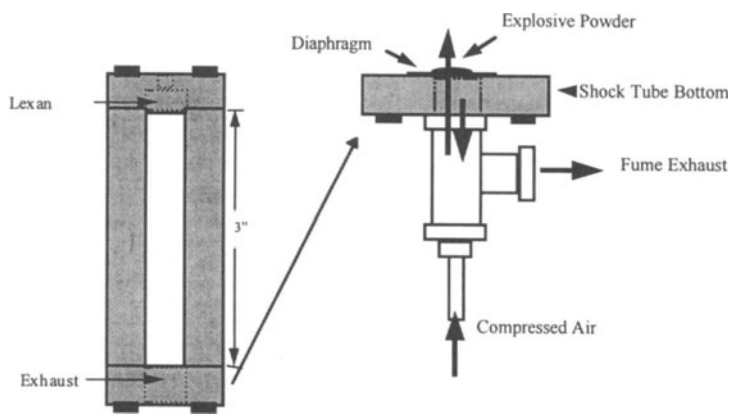

Figure 5. Shock tube design, illustrating the clear 3" optical access and method by which a dispersion is obtained.

jet of compressed air through the exhaust port of the shock tube, thus disturbing any particles in the chamber. The particles are placed and contained in the tube by means of a fibrous diaphragm placed at the bottom of the shock tube, before the exhaust port. When the blast of air is introduced, the particles are blown up into the tube by air passing through the diaphragm and are contained in that volume.

As noted earlier, prior study of explosive dynamics at Hopkins has resulted in the design and assembly of a White Cell optical delay line. The White Cell is a purely optical configuration capable of outputting up to 10 spatially and temporally separated pulses of equal irradiance for a single input laser pulse, with a temporal pulse separation ranging from 28.6ns to 169ns. For purposes of the shock tube study using the holographic technique reported here, the output of the White Cell must be conditioned such that each output beam satisfies three conditions. First, the individual beams must be expanded to provide as much illumination of the clear aperture of the shock tube as possible. This is in order to get as much information about what is happening in the shock tube as possible. Second, the beams passing through the shock tube must be drawn to a focus at the film plane. In order to record a filtered hologram, the Fourier transform of the object field (the focus) must be at the film plane. Finally, the focuses of the beams must be separated in space enough to avoid overlap (cross-talk) of the holographic exposures.

The optical system designed for this purpose, excluding the White cell, is illustrated in Figure 6. This figure shows five temporally and spatially separated beams, which are split into object and reference legs for holographic recording. The object beams are steered by five small mirrors into a negative lens, where the steering mirrors are arranged such that the beams exiting the negative lens are roughly parallel. A collimating lens is placed immediately prior to the shock tube which causes the five beams to intersect in the shock tube interior. Immediately following the shock tube, a high quality Fourier transform lens is used to separate the five beams and draw each to a sharp focus at the film plate. The reference beams are adjusted so that each intersects with its appropriate object beam at the film plate.

For these experiments, a particulate cloud was dispersed in the shock tube using compressed air. To initiate detonation in the dispersion, an IR laser pulse was brought to a focus in the center of shock tube interior. After an adjustable delay, the holographic system

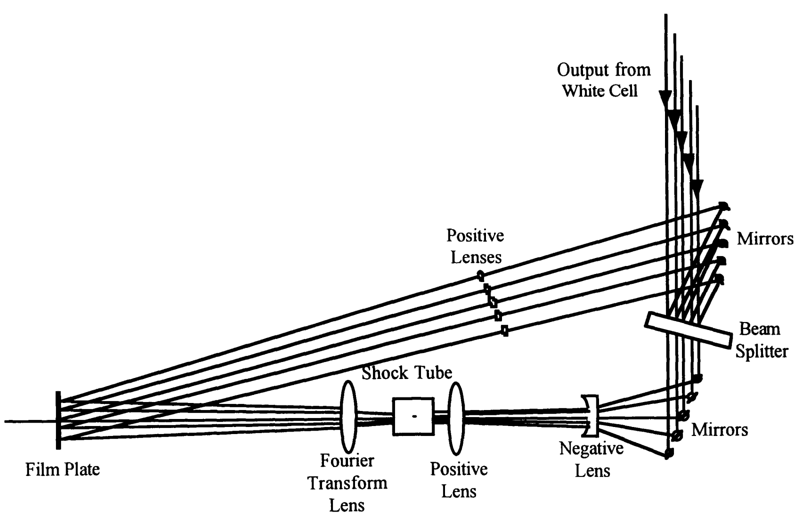

Figure 6. Experimental configuration for recording high-speed, time-resolved, filtered holograms of a dispersed particle detonation using the Fourier holography technique.

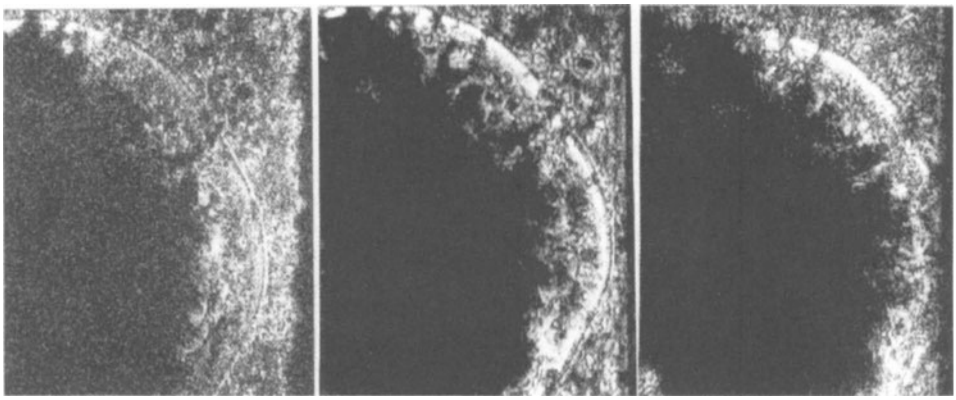

Figure 7. Holographic reconstructed images of detonation in a dispersed particle explosive, recorded 10.60, 10.77, and 10.94 microseconds, respectively, after detonation initiation.

was used to record the events as they transpired in the shock tube, typically with a 169ns interval between exposures.

Typical holographic reconstructions using this technique are shown in Figure 7. The first of the three images presented was recorded 10.6μs after a dispersion was detonated, with the successive frames recorded at 169ns intervals. Individual particles can be seen in various stages of detonation. The observed primary shock front moves with a velocity on the order of one millimeter per microsecond (Mach 3).

CONCLUSIONS

As evident from the experimental results, the high-pass filtering achieved through this technique can be quite pronounced. Application of the method for high-pass filtering of amplitude-based transmission functions and phase object has been demonstrated. Additionally, this technique has been adopted in conjunction with a high-speed time-resolved holographic technique to investigate detonation dynamics in dispersed particle explosives.

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